Monitoring laser weld quality

Due to the increasing use of high-power CO_2 lasers for welding automotive transmission components at Chrysler (now DaimlerChrysler Corporation), executive board members realized the significance of developing a real-time weld process monitor to ensure that its high quality automotive standards are maintained. This led to a mandate that a monitoring system would be developed and installed on all laser welding systems at Chrysler.

Accepting the challenge to develop the technology, a team at Argonne National Laboratory headed by Dr. Keng Leong, was given mandatory specifications that the system had to be real time, user friendly, low cost, robust, and above all, reliable. Dr. Leong brought Spawr Industries Inc. (Lake Havasu City, AZ) into the program to design an optical package for integration with the electronic package developed by the Argonne team. The final system design met all of the mandated specifications and, in fact, was awarded a patent.

DaimlerChrysler adopted the technology, installing several systems in the Indiana Transmission Plant (ITP—Kokomo, IN), where the systems have been running successfully for several years. This success record convinced DaimlerChrysler to use these systems in its new manufacturing plant (ITP2) scheduled to go on-line in late 2003. This plant utilizes five TRUMPF (Farmington, CT) CO_2 lasers that have power levels of 3.5 kW and 5 kW, each integrated with German-built weld stations made up of twin spindles to increase capacity throughput. Weld monitoring is by the Argonne/Spawr system.

The weld monitor identifies bad welds in real time and rejects them from the production line. The function of the weld monitor is based on the collection of infrared light emission directly from the weld pool, and the conversion of these emissions to an electrical signal that can be analyzed by computer software and displayed in a voltage amplitude versus time format. Figure 1 illustrates the correlation between the analyzed trace signature and weld penetration depth with various anomalies that frequently exist in welds. Note the high amplitude spike (weld void), representing overheating from poor thermal conduction in the keyhole, and increase in the signal noise level when contamination is present. The negative fallouts in signal amplitude occur and correspond to a reduced thermal penetration, which often occurs when laser power is momentarily lost or reduced. A benefit not shown in Figure 1 is the off-seam detection capability. In addition to identifying and accepting good welds and rejecting bad welds, the system's relationship between signal signature and the weld's physiology offers a powerful real-time diagnostic tool for improving process parameters.

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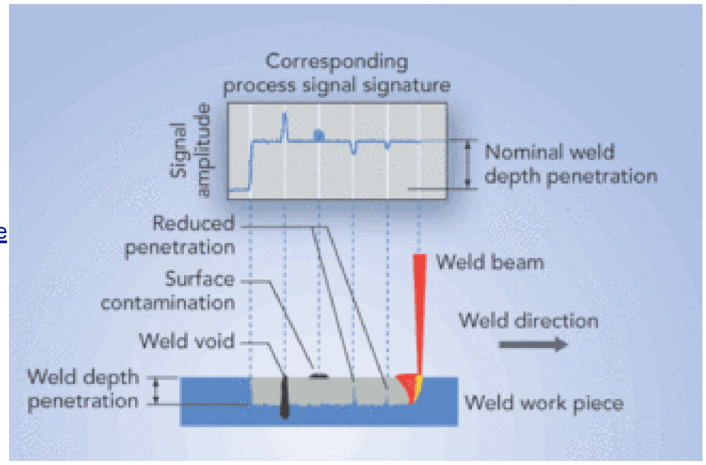

Figure 1. Correlation between physical weld and display structure.

Problems occurred when the new ITP2 plant was to go on-line. The weld monitor appeared to be lacking in sufficient resolution to identify bad welds (weld depth penetration and off-seam location), when integrated with the laser and the beam delivery system on the integrated weld station.

The new weld stations use very high beam quality CO_2 lasers with beam delivery in a high-quality 250mm focal length parabolic focus mirror that delivers a near diffraction limited focused spot. By replacing the parabolic focus mirror with a specially designed mirror, which produces an aberrated focus spot, the weld quality increased, the weld monitor resolution increased, and the problem was resolved.

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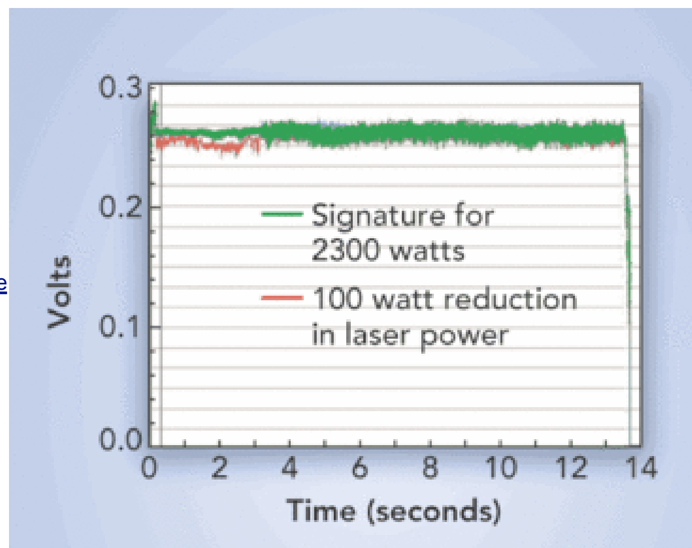

Figure 2. The overlaid signatures of two separate welds illustrate original condition with original parabolic focus mirror. Green is signature for 2300 watts. Red indicates a 100-watt reduction in laser power.

Figure 2 shows the original weld signature, prior to changing out the parabolic focus mirror, and the inability to adequately resolve laser power changes. The first three seconds of the weld is a 360° rotation pre-weld of the part at 2.3 kW CW with penetration of 0.56 mm. After the first three seconds the rate of rotation is slowed down until the part makes another complete 360o rotation for a total of approximately 13.5 seconds. The first three seconds is with a pre-weld feed rate at 10,000 mm/min. The second rotation for the weld is at a feed rate of 3,000 mm/min.

Note the upward shift of the signature amplitude in Figure 3 indicating weld penetration depth has increased (after the first three seconds) after installation of the new focus mirror, but there is no increase in the original weld trace, using the parabolic focus mirror (see Figure 2). After the three-second pre-weld the signature only becomes very broad, diagnostically indicating an increase in noise and poor weld quality.

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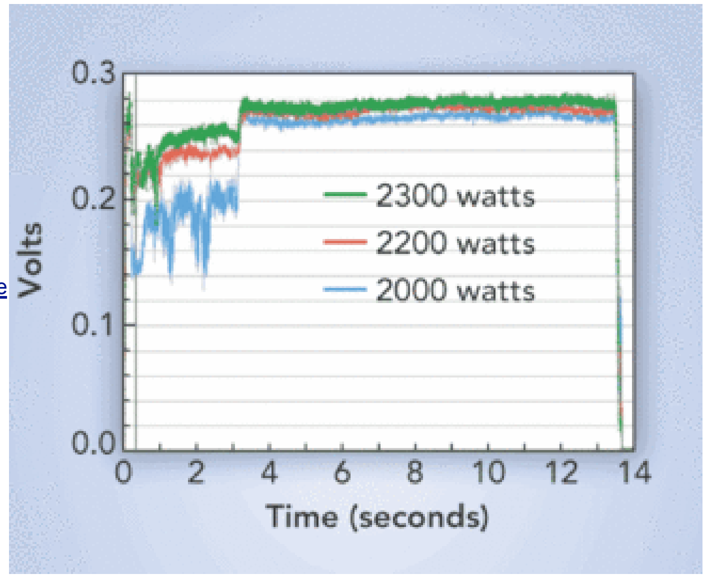

Figure 3. The overlaid signatures of three separate welds illustrate laser power changes with new focus mirror. Green represents 2300 watts. Red represents 2200 watts. Blue represents 2000 watts.

Figure 3 shows the improvement in resolution with the new focus mirror. Both 300W and 100W changes are sufficiently noticeable to indicate rejection of the weld. Figure 4 shows resolution to adequately resolve off-seam locations of 0.50mm and 0.25mm.

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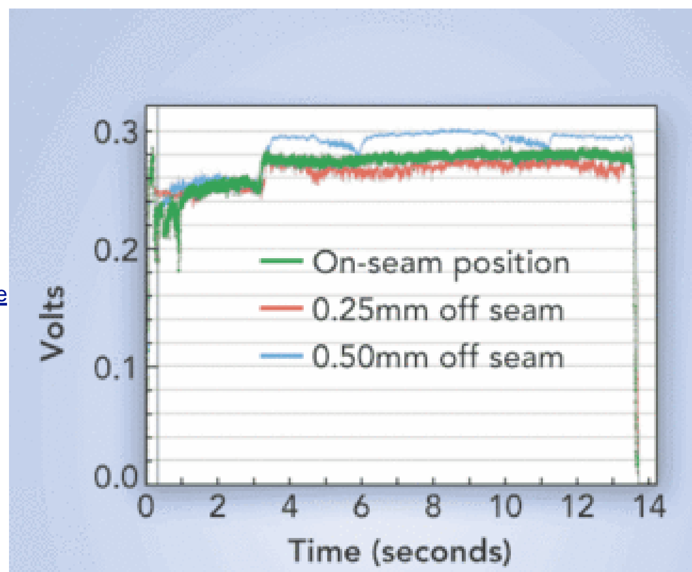

Figure 4. The overlaid signatures of three separate welds with new focus mirror illustrate off-seam positions at constant 2300 watts. Green represents on seam position. Red represents 0.25mm off seam. Blue represents 0.50mm off seam.

The new focus mirror produces better welds because it reduces the intense irradiance level and non-uniformity of the beam at focus. The laser beam has a TEM_{00} mode with an M^2 of 1.11. The original parabolic focus mirror produces a near diffraction limited spot size of approximately 0.33 mm diameter. At 2.3 kW the average irradiance at focus is approximately 2.7 MW/cm^2. However, because most of the power (about 86 percent) is contained in the center of the beam, between the $1/e^2$ points, the peak power in the focus (within the central 0.25 mm diameter) exceeds 4 MW/cm^2. This high irradiance level produces volatile overheating and turbulent flow in the keyhole, which reduces uniform thermal diffusivity, leading to stress and fractures. Evaporation of metal also occurs and produces poor bead surface quality. The net effect is a very noisy low-resolution trace signature on the weld monitor display. This problem is also evident in the cross-sectional weld specimens in Figure 5, which were made with the original parabolic mirror at 2.3 kW. The hourglass profiles are historically present only when the focus beam uniformity profile is not optimum. Figure 6 shows the weld profile produced after replacing the parabola with the new mirror, which re-shapes the focus into an elliptical spot and reduces the peak irradiance.

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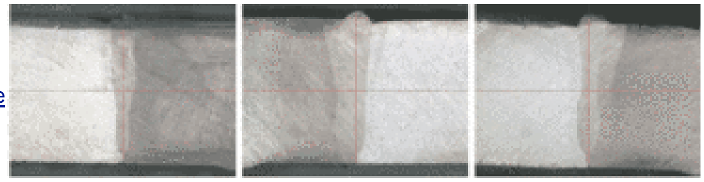

Figure 5. Illustrations of weld cross sections display evidence of unstable keyhole formation during welding, which results in high signal noise on the weld monitor.

Poor weld parameters produce poor quality welds and poor weld monitor signal resolution. Diagnostically, low weld monitor resolution indicates less than optimum weld quality. Before the development of the Argonne/Spawr weld monitor there was no way to visualize the real time impact difference between a high-quality, well-focused beam and an aberrated beam. By using the weld monitor diagnostically, improvements to weld parameters were realized, and better welds were produced by being able to see real time changes in performance between two types of focus mirrors.

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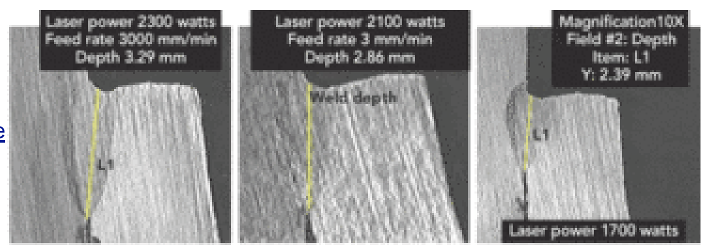

Figure 6. Cross section samples of three welds at various laser power settings: 2300-watt full penetration weld on seam, 2100-watt full penetration, and 1700-watt welds.

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